

## Experimental observation of $m/n = 1/1$ mode behaviour during sawtooth activity and its manifestations in tokamak plasmas\*

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### Abstract

To shed some light on the development of the fast  $m/n = 1/1$  precursor to the sawtooth crash and its influence on plasma transport properties in the vicinity of the  $q = 1$  surface, series of dedicated experiments have been conducted on the Tore Supra and TEXTOR tokamaks. It has been concluded that, before a crash, the hot core gets displaced with respect to the magnetic axis, drifts outwards by as much as 8–10 cm and may change its shape. Observation of the magnetic reconnection process has been made by means of electron cyclotron emission diagnostics. The heat pulse is seen far outside the inversion radius. The colder plasma develops a magnetic island on the former magnetic axis, after the hot core expulsion. Different kinds of behaviour of the  $m = 1$  precursor before the crash, with respect to the displacement of the hot core and the duration of the oscillating phase, have been observed. An ideal kink model alone cannot be used for explanation; therefore, resistive effects play an important role in the mode development. Possible mechanisms that lead an  $m = 1$  mode to such behaviour, and their links to the change in the central  $q$ -profile, are discussed.

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Results have been discussed in the light of various theoretical models of the sawtooth.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Sawtooth oscillations in the tokamak plasma are often preceded by a fast (with respect to the sawtooth period) magnetohydrodynamic (MHD) precursor with  $m/n = 1/1$  as the dominant mode, in which  $m$  and  $n$  are poloidal and toroidal numbers, respectively. The most famous model to explain the sawtooth crash as a periodic magnetic reconnection of plasma inner regions with different magnetic helicity was introduced by Kadomtsev [1]. Later, a few experimental features that contradict the Kadomtsev model were found. It has been shown that the central value of the safety factor  $q_0$  may stay below one after the crash [2], and the crash time can be shorter than predicted by the model [3]. Several explanations have been put forward to clarify these discrepancies. Some of them have attempted to modify the Kadomtsev model by including incomplete reconnection and the very important effect of magnetic shear around the  $q = 1$  surface [4], finite pressure effects [5], or some other mechanisms [6, 7]. Others have introduced completely different models, such as an ideal  $m = 1$  mode development with a reconnection during the ramp phase proposed to explain JET observations [8], or implied a three-dimensional reconnection to explain the sawtooth crash [9]. However, so far no reliable model for the internal disruption in general and for the sawtooth oscillation in particular has been found.

On the Tore Supra and TEXTOR tokamaks, series of experiments have been conducted to shed some light on the fast  $m/n = 1/1$  mode topology and its influence on transport properties in the plasma centre. Before the sawtooth crash, the hot core is pushed outwards and rotates a number of periods, with respect to the magnetic axis. Evidence that the displaced hot core may reshape at this stage has been obtained. A magnetic island with the colder plasma inside is formed on the former magnetic axis. Depending on the value of the hot core displacement, the duration of the oscillating phase and the presence/absence of postcursor activity, two kinds of  $m = 1$  precursor evolution can be distinguished. Observation of the magnetic reconnection process has been made by electron cyclotron emission (ECE) at the LFS. It is suggested that the  $m = 1$  mode cannot be described as an ideal kink only [8], and resistive effects play an important role in development of the mode. Possible mechanisms that influence the  $m = 1$  mode behaviour before and after the sawtooth crash and their links to the evolution of the central  $q$ -profile will be discussed in this paper.

This paper is organized as follows. In section 2, the diagnostics used for analysis of the  $m/n = 1/1$  mode behaviour both on TEXTOR and Tore Supra are described. In section 3 experimental observation of the mode before and after the sawtooth crash as well as the topology of the mode are presented. The influence of the  $q$ -profile and magnetic shear on the different manifestations of the  $m = 1$  mode during the sawtooth activity is discussed in section 4. Finally, a conclusion is given in section 5.

## 2. Diagnostic setup

The Tore Supra tokamak ( $R_0 = 2.40$  m,  $a = 0.72$  m,  $B_T \approx 4$  T, circular cross-section) is equipped with a 32-channel ECE radial heterodyne radiometer (78.5–109.5 GHz in

O-mode, 94.5–126 GHz in X-mode, 1 GHz spacing between adjacent channels, sampling rate 1–86 kHz) [10]. The radiometer is absolutely calibrated by means of a hot source. A measurement error of the profile ECE is  $\Delta T_e/T_e = 1\%$ . A set of fast/slow soft x-ray (SXR) cameras (21 horizontal and 37 vertical viewing chords) allows for a poloidal reconstruction of the plasma region  $\pm 60$  cm above and below the midplane [11]. An X-mode heterodyne density fluctuation reflectometer (105–155 GHz,  $B_T > 3$  T is required) and two X-mode density profile reflectometers (50–75 and 75–110 GHz) are being used to study fast (up to 500 kHz) MHD phenomena throughout the plasma cross-section [12]. During lower hybrid (LH) heating, the fraction of non-inductively driven current can be quite significant and needs to be included in the  $q$ -profile calculations. Because a hard x-ray (HXR) emission profile is related to the LH driven current profile, an HXR tomography system helps to obtain a proper estimate of the  $q$ -profile in discharges with lower hybrid current drive (LHCD) with relatively good spatial (5 cm) and temporal (2–16 ms) resolution [13].

On the TEXTOR tokamak ( $R_0 = 1.75$  m,  $a = 0.46$  m,  $B_T < 2.9$  T, circular cross-section), the radial/vertical set of ECE (second harmonic, X-mode) diagnostics has been used to study the development of the  $m/n = 1/1$  mode. The radial set consists of an 11-channel radiometer (105–145 GHz, sampling rate up to 25 kHz) with a combined LFS/HFS antenna, three six-channel spectrometers (104–114, 125–130, 133–148 GHz, 50 kHz) and a 16-channel heterodyne radiometer (96–146 GHz, 2 MHz) [14]. A 16-channel ECE-imaging system is used to monitor a vertical chord in the plasma, with a spatial resolution of about  $1 \times 1$  cm<sup>2</sup> in the poloidal plane. The radial position of the chord can be varied by changing the frequency of the local oscillator [15]. The 11-channel radiometer is absolutely calibrated by means of a hot–cold source, while other ECE diagnostics used for this paper are cross-calibrated with respect to the 11-channel radiometer.

### 3. Experimental observation of $m/n = 1/1$ mode in plasmas with sawteeth

On Tore Supra, the  $m/n = 1/1$  mode behaviour in sawtooth plasmas has been studied for ion cyclotron resonance heating (ICRH), LHCD and purely Ohmic regimes. On TEXTOR, shots with Ohmic, ECRH, ICRH and neutral beam injection (NBI) featuring the  $m = 1$  mode activity have been investigated. In this paper, only fast MHD precursors to sawteeth that manifest themselves as periodical oscillations before and/or after the crash, will be discussed. We will leave out any sawteeth that do not clearly show fast  $m = 1$  mode activity, such as, for example, monster sawteeth.

#### 3.1. The $m = 1$ mode manifestations on Tore Supra and TEXTOR

In the literature, the  $m/n = 1/1$  mode activity before or after the sawtooth crash is often called *pre-* or *post-*cursor, respectively, [9, 16]. In reality, this is a very sketchy classification because oscillations may survive the crash and continue with the same frequency and amplitude for a long time after it. Even during the sawtooth rise, a so-called compound crash (or *midcursor* [9]) can exist under certain plasma conditions. Therefore, it is suggested that we will discuss the different  $m = 1$  mode manifestations during sawtooth activity and will use the words ‘*precursor*’ and ‘*postcursor*’ only for reasons of clarity. In other words, in all investigated cases, the same  $m/n = 1/1$  mode will appear.

In Ohmic and ICRH phases of Tore Supra shots with strong sawtooth activity (Ohmic: central density  $3.0\text{--}5.0 \times 10^{19}$  m<sup>-3</sup>, plasma current 1.2 MA; ICRH: power up to 1.7 MW, central density  $4.5\text{--}6.0 \times 10^{19}$  m<sup>-3</sup>), two kinds of the  $m = 1$  precursor behaviour are distinguished. The first one looks like a ‘classical’ precursor, and is characterized by a displacement of

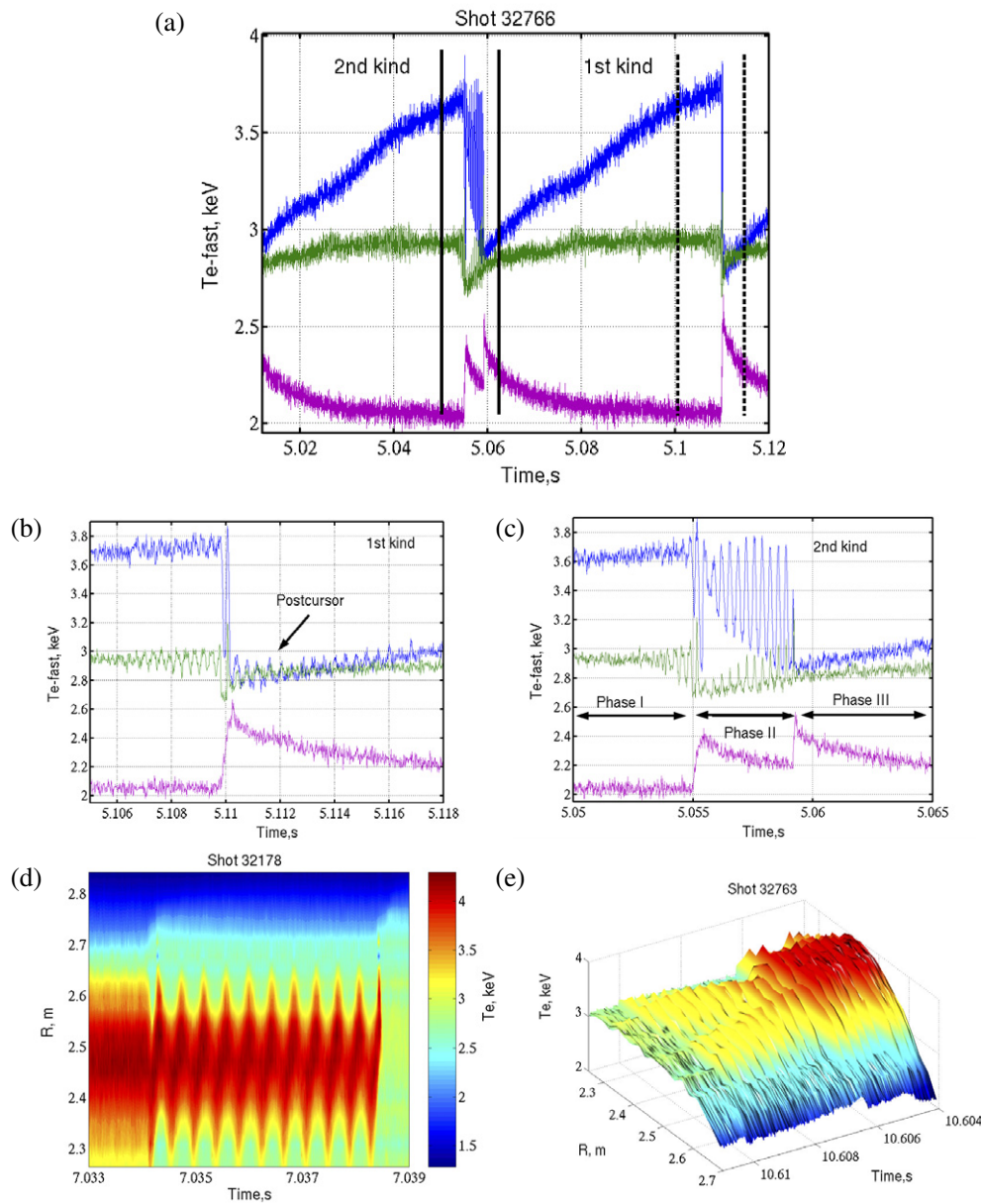
the hot core by about 2–3 cm (as estimated from the temperature perturbation measured by ECE and the reconstruction of the SXR emission), with respect to the former position of the magnetic axis. Because the displaced hot core rotates with the plasma, ECE time traces show periodic oscillations with the amplitude corresponding to the difference in temperature between the plasma inside and outside the core (figures 1(b) and (c)). This phase can last until very close to sawtooth collapse, and the postcursor oscillations can exist for up to 10 ms, implying the reconnection process is not completed (figure 1(b)).

The second kind is shown in figure 1(c) and exhibits somewhat different behaviour. It starts similar to the first kind described earlier (phase I), then the crash event occurs and the hot core is shifted by 5–8 (sometimes 10) cm in just 100–150  $\mu$ s. For Tore Supra shots reported in this paper, the inversion radius  $r_{\text{inv}}$  is typically 15–20 cm (the definition of the inversion radius will be given in section 3.3). However, oscillations still continue after the crash, and the temperature and density inside the shifted hot core do not experience significant changes. This oscillating phase may last up to several milliseconds. During phase II, the hot core displacement increases steadily until the second crash (figure 1(e)) or may stay constant as a saturated precursor (figure 1(d)). It appears to be that the displaced hot core may survive a few successive crashes. In the end, after the final crash, no or strongly reduced in amplitude postcursor oscillations are observed for a few milliseconds (typically 3–4 ms, phase III). One may assume that in this case reconnection is almost complete. Because there is a linear phase during the precursor evolution, and lacking the polarimetry measurements, no good estimation of the growth rate can be made on Tore Supra now. The frequency of appearance and the duration of the oscillating phase for the second kind of precursor behaviour show some correlation with the change in the plasma density (see figure 2). Interestingly, different  $m = 1$  mode activity types in ICRH and Ohmic plasmas may be observed even in two successive sawteeth.

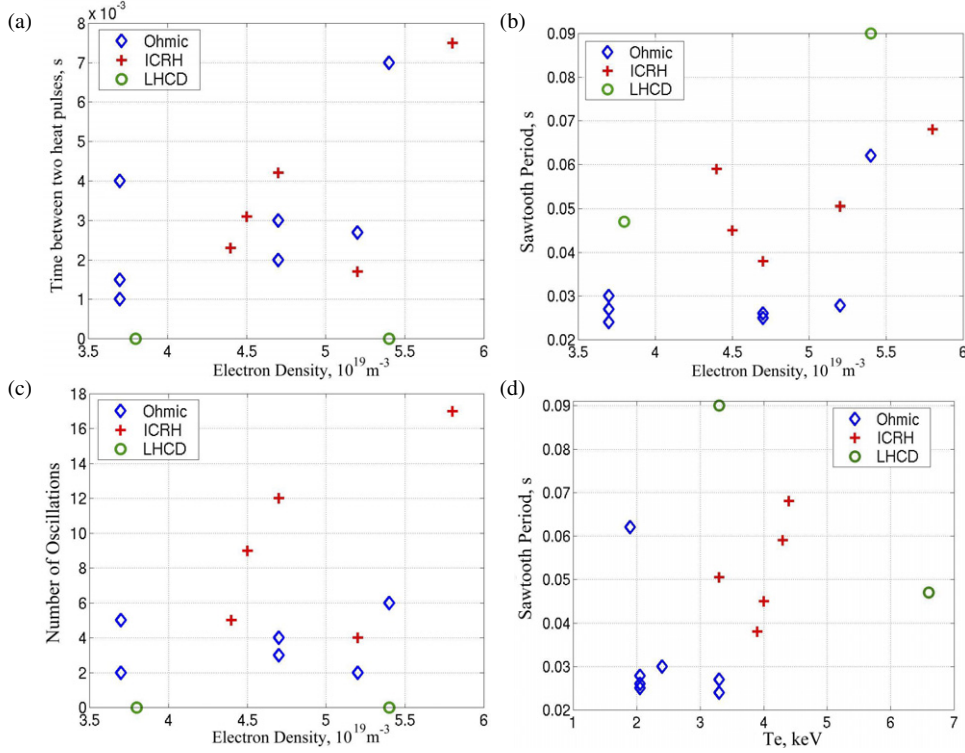
Evolution of the compound, or ‘mid’-crash (midcursor) generally resembles one of two kinds of  $m = 1$  mode behaviour described above. There can be not only one, but also two or even three compound crash events in the course of the ‘main’ sawtooth rise, as shown in figure 3. This implies that mechanisms responsible for different  $m = 1$  mode manifestations can be as well responsible for the behaviour of the midcursor too.

When only LHCD is applied with the power above 2 MW, the second type of  $m = 1$  mode behaviour has never been observed. Nevertheless, the saturated ‘mid’-cursor can still be present. The influence of LHCD on the central  $q$ -profile and its role in the  $m = 1$  mode behaviour will be discussed in section 4.

On TEXTOR, precursors similar to those of the first type in Tore Supra have been observed in various Ohmic, ECRH and NBI-heated discharges with central densities below  $2.5 \times 10^{19} \text{ m}^{-3}$ . Sawtooth precursors analogous to the second kind of  $m = 1$  mode behaviour have been detected in plasmas that are very close to the  $\beta$ -limit, in which more than 1.8 MW of power has been injected by means of two NBIs (co- and counter), and two ICRH antennas (figure 4). For this particular shot, central density has reached more than  $4 \times 10^{19} \text{ m}^{-3}$ . The first heat pulse is correlated with the sudden growth in the temperature oscillation amplitude at about 1.72 s; however, it is not as pronounced as in the Tore Supra case. From the polarimetry measurements, the growth rate of the  $m = 1$  mode is estimated to be up to  $600 \text{ s}^{-1}$  and the radial displacement of the hot core by 5 cm just before the sawtooth crash ( $r_{\text{inv}} = 15 \text{ cm}$ ). The frequency of the oscillations is strongly influenced by the rotational momentum exerted on the plasma by NBI. These studies have been made on TEXTOR in detail [17] and will not be repeated here.



**Figure 1.** Two kinds of different  $m = 1$  precursor behaviour are present in two successive sawteeth in the ICRF-heated plasma on Tore Supra ((a) ECE fast acquisition). The first kind of  $m = 1$  mode manifestation shows postcursor activity ((b) black arrow). Three phases in the development of the second kind of  $m = 1$  precursor can be distinguished (c). Only the most representative time traces have been selected. An example of the saturated precursor type is given in (d) for a different shot. In contrast, a surface plot ((e) shot #32763) shows how the hollow temperature profile is building up in the plasma centre from 10.606 to 10.61 s owing to the steadily increasing displacement of the hot core.



**Figure 2.** The time between the two heat pulses (a), number of oscillations in between these heat pulses (c), and duration of the sawtooth period (b) and (d) versus central electron density and temperature for different heating regimes on Tore Supra.

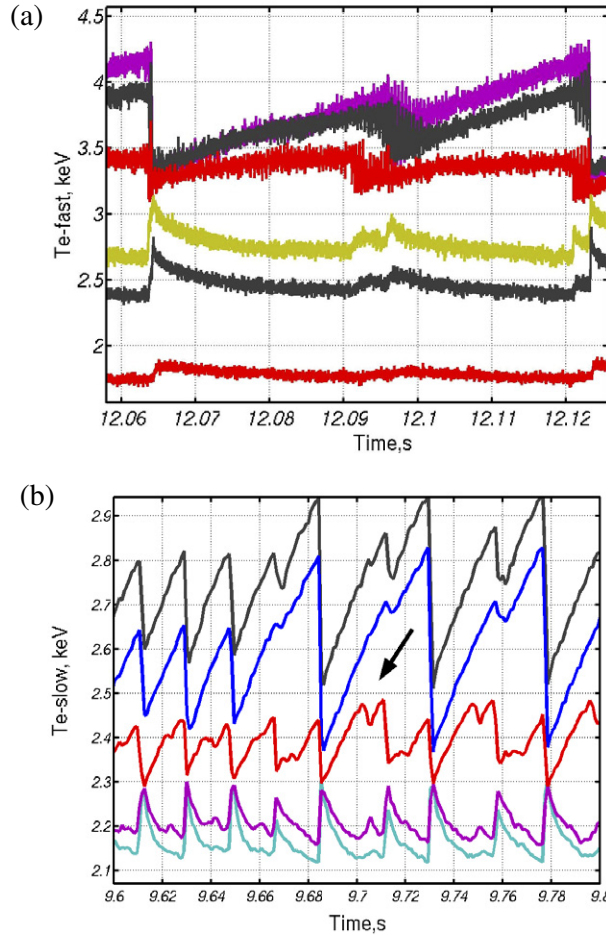
### 3.2. Typical crash times

Estimations of crash times were made for both kinds of  $m = 1$  precursor behaviour on Tore Supra. Because the ECE time traces inside the inversion radius are highly modulated by the oscillating precursor, it is difficult to determine the crash times precisely. Figure 5(a) shows the behaviour of channels inside and outside the inversion radius in different phases of the crash for the same shot and time window as in figure 1(c). An inverted sawtooth rise on the ECE channel that monitors the plasma just at the inversion radius has been used to determine the crash time (time windows B, C, E and F in figure 5(a)), in accordance with the method reported in [18]. A typical crash time for the first kind of the precursor activity and for the ‘first crash’ with the second kind is found to be about  $150 \mu\text{s}$ . A typical ‘second crash’ time is somewhat shorter than for the ‘first crash’ and is of the order of  $100 \mu\text{s}$ . For the same  $m = 1$  precursor activity type, no significant difference in crash times between different heating regimes has been observed. For a typical Alfvénic time  $\tau_A \approx 2 \times 10^{-7} \text{ s}$ , and a resistive time  $\tau_R \approx 1 \text{ s}$  (for  $r \leq r_{q=1}$ ), a theoretically calculated (according to the Kadomtsev model) crash time for Tore Supra is

$$\tau_{\text{Kad}} \approx \sqrt{\tau_A \tau_R} \approx 450 \mu\text{s}. \quad (1)$$

Thus, on Tore Supra, the measured crash times are shorter than the calculated ones by a factor of 3–4.



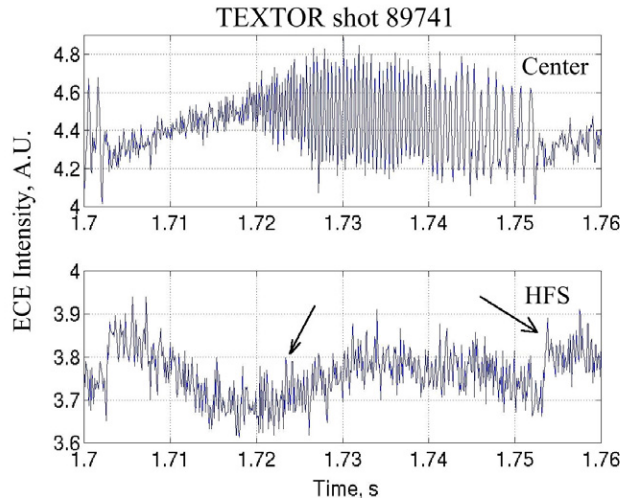


**Figure 3.** A typical ‘single’ compound crash with strong  $m = 1$  mode activity between 12.09–12.1 s at Tore Supra ((a) ECE fast acquisition), and a ‘double’ compound crash ((b) black arrow; ECE, slow acquisition). In (b), the central channel at  $R = 2.42$  m is shown in blue. The temperature at the HFS (upper black trace) is influenced by the downshifted second harmonic non-thermal ECE.

On TEXTOR, the typical crash times for NBI-heated discharge are of the order of  $40\text{--}80\text{ }\mu\text{s}$ , much smaller than that predicted by the Kadomtsev model. High temperature tokamak plasmas such as Tore Supra and TEXTOR are not well described by resistive MHD. A semicollisional [19] or ion kinetic [20] regime is probably more appropriate for the  $m = 1$  stability studies on both machines; therefore, it was expected that the measured crash times are smaller than that calculated according to Kadomtsev model.

### 3.3. Electron temperature profiles in different crash phases: heat pulse propagation

To describe the heat transfer process during the sawtooth crash we will use the following terminology for inversion and mixing, or reconnection, radii. The inversion radius on both machines can easily be determined as the radius where two temperature profiles, before and



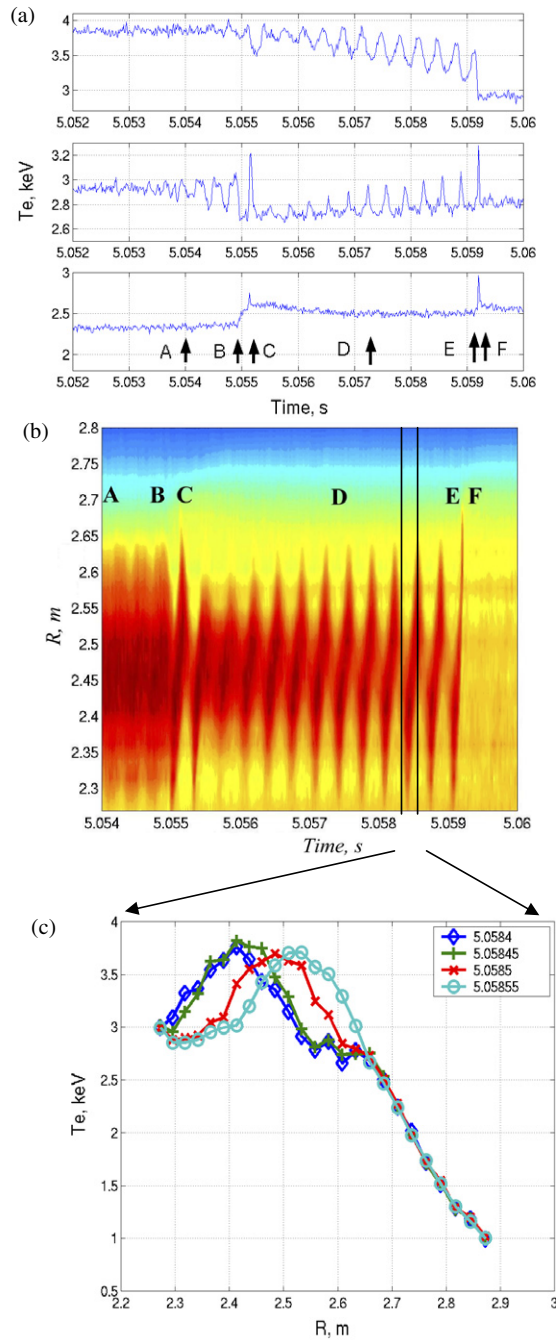
**Figure 4.** TEXTOR shot #89741 showing behaviour of the  $m = 1$  mode similar to the second kind of precursor manifestation on Tore Supra, as observed by ECE. Black arrows indicate times of the first (1.725 s) and the second (1.753 s) crashes.

after the crash, cross (see figures 1(d) and 6(f)), or is estimated from the maximum radial extent of the temperature perturbation caused by the  $m = 1$  mode. Both for Tore Supra and TEXTOR, the inversion radius is assumed to coincide with the  $q = 1$  surface. The standard ('classical') definition of the mixing radius as the radius to which the sawtooth crash flattens the temperature profile has been given by Kadomtsev [1], and is illustrated by a dashed arrow in figure 6(f). However, it will be shown that the radius, to which there is a response of the electron temperature to the crash, can exceed the one predicted by Kadomtsev. Therefore, we will use in the remainder of the paper the definition of the mixing radius given by Nagayama *et al* in [9], as shown in figure 6(f) by a solid arrow.

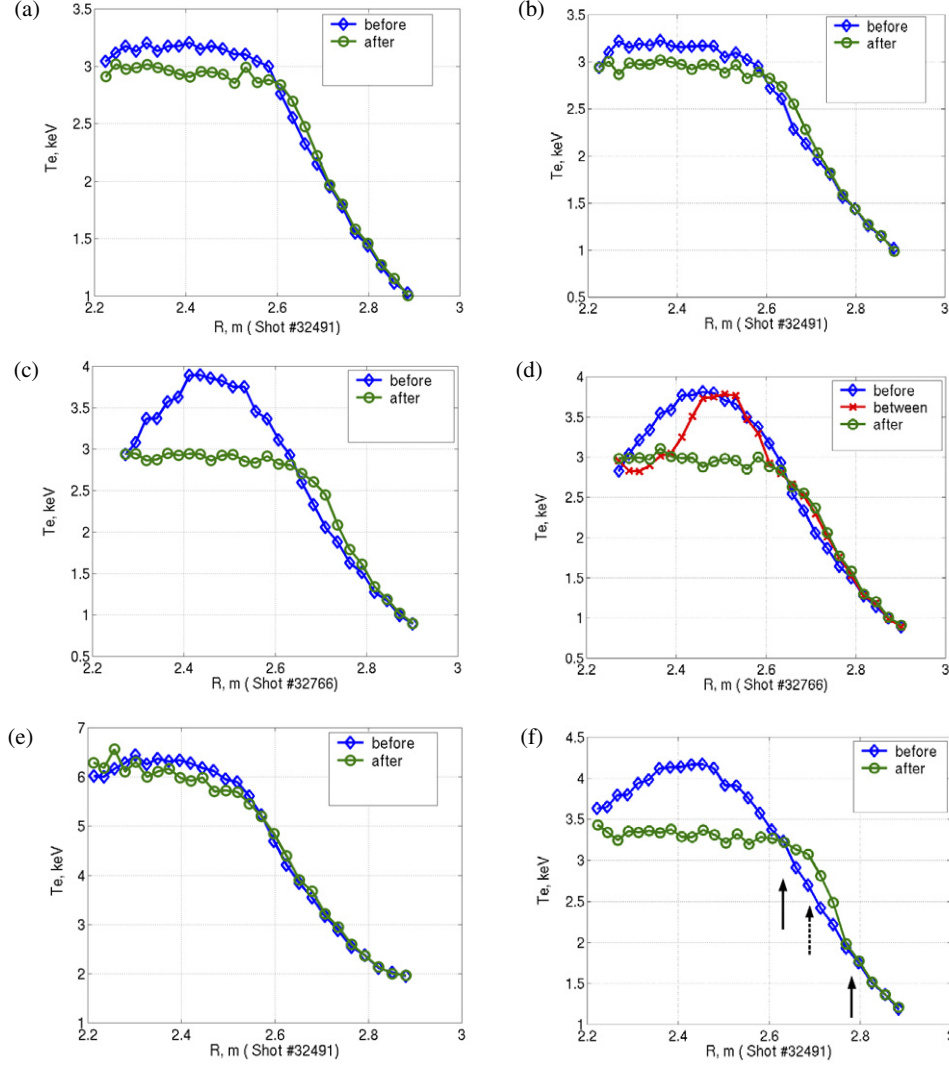
Figure 6 shows electron temperature profile before and after the crash for Ohmic (figures 6(a) and (b)), ICRH (figures 6(c), (d) and (f)) and LHCD (figure 6(e)) plasmas in Tore Supra with strong  $m = 1$  mode activity. For profiles marked as figures 6(b), (d) and (f), crashes with the second kind of  $m = 1$  precursor behaviour have been selected, while for the others the first kind has been chosen. It can be seen that for ICRH precursors, the central temperature drops by almost 20–25%, compared with 10–12% for Ohmic and with 3–5% for LHCD plasmas. Typical values of  $\beta_p$  are estimated to be about 0.35 for ICRH, 0.18 for Ohmic and 0.21 for LHCD plasmas. For all these shots the value of the safety factor at the plasma edge,  $q_a$ , was about 3.9.

The drop in temperature also varies for the sawtooth plasmas with the same injected ICRH power but with different kinds of precursor behaviour. Even for two successive crashes in Ohmic phase with different  $m = 1$  mode activity, a difference of 2–5% in  $\Delta T_e$  can exist (for the typical error in the electron temperature measurements by ECE of about 1%). It is important to mention that the mixing radius for ICRH crashes is somewhat larger than that for Ohmic ones. For the crash shown in figure 6(c), the heat is being transferred outside the inversion radius at  $R = 2.62$  m to the mixing radius at  $R = 2.8$  m. Therefore, the mixing radius on Tore Supra can be as large as 50% of the minor radius at the LFS, in agreement with measurement made on TFTR [9, 21], where the extended temperature perturbation has been observed far beyond the 'classical' (Kadomtsev) mixing radius. As can be seen in figure 6,





**Figure 5.** Crash phases on Tore Supra as observed by ECE channels inside and outside the inversion radius (a) and electron temperature contour plot for the whole phase (b) for the same shot #32766 as in figures 1(a)–(c). Typical electron temperature profiles for the  $m = 1$  precursor rotation period are shown in (c). Letters A to F aid the identification of different times of the precursor evolution between plots (a) and (b).



**Figure 6.** Electron temperature profiles for two  $m = 1$  mode activity types before and after the crash (left column—the first type, right column—the second type) in different heating regimes ((a) and (b)—Ohmic, (c), (d) and (f)—ICRH, (e)—LHCD) on Tore Supra: (a), (b), (e) and (f) correspond to the same shot as in figure 4, (c) and (d) correspond to the same shot as in figures 1, 2(a), (b) and 6. For reasons of clarity, the  $q = 1$  (left solid arrow) and mixing radii (for both definitions; dashed (Kadomtsev) and right solid (Nagayama) arrows) are only shown in (f). Profiles shown in this figure are typical of many cases in Tore Supra.

the post-crash temperature profiles are flat or slightly rounded. So far, no evidence of the hot ring at the end of the crash similar to what has been seen on TCV in the plasmas with central ECRH [22], has been obtained on Tore Supra in LH and ICRF-heated plasmas. On TEXTOR, the post-crash temperature profiles in Ohmic and NBI-heated plasmas are similar to those on Tore Supra. A hollow temperature profile in off-axis ECR-heated discharges has been recently observed by means of ECE diagnostics; however, no clear link to the sawtooth activity has been detected.

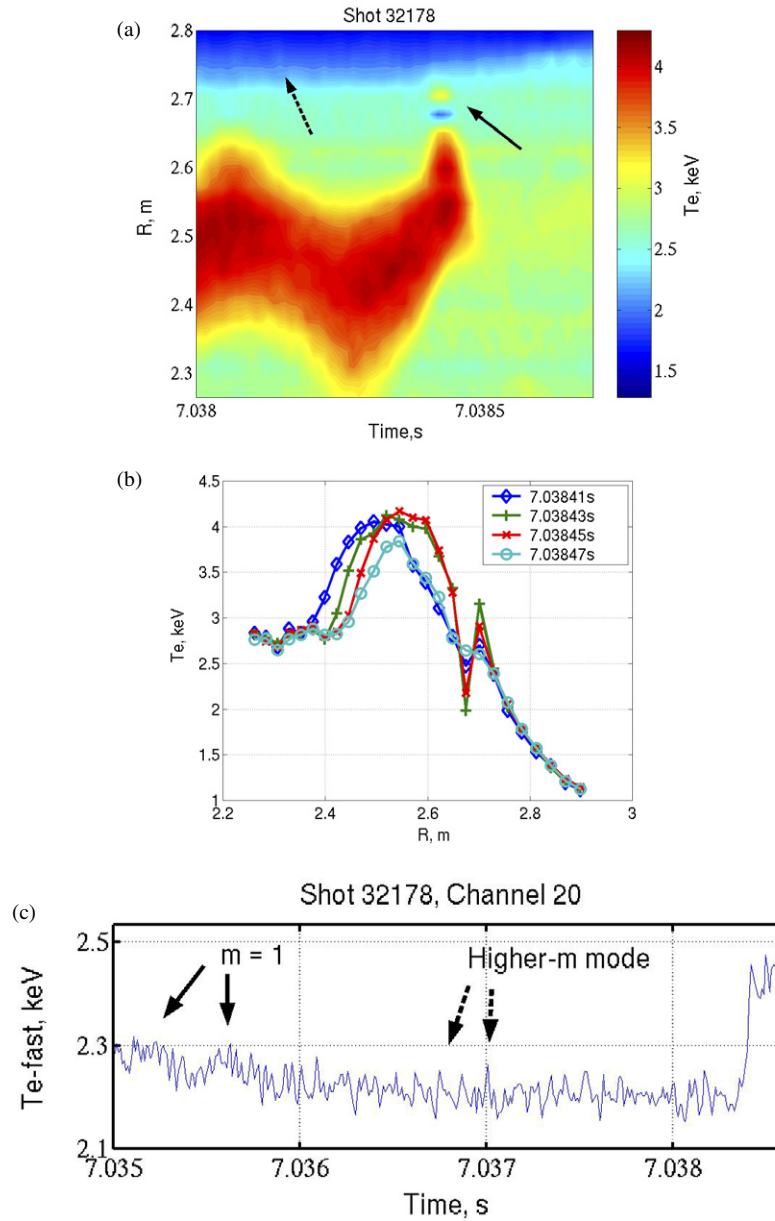
At TFTR, a distortion of the electron temperature in high- $\beta_p$  plasmas is observed during the phase with the oscillating  $m = 1$  precursor by Park *et al* [5]. This distortion is asymmetrical and appears as a bulge towards the LFS of the machine. It has been suggested that the origin of this phenomenon is similar to the ballooning mode mechanism. The asymmetrical distortion pushes the plasma outside the ‘classical’ mixing radius and induces magnetic islands with different  $m$  and  $n$  numbers at various surfaces. Formation of these islands leads to the ergodization of the magnetic field and, thus, to the modification of the heat transport in the region. On Tore Supra, though  $\beta_p$  is much smaller than in TFTR experiments we refer to, evidence of the higher order modes on the onset of the  $m = 1$  precursor has been obtained. Measurements were made by means of the fast profile ECE and the newly installed correlation ECE [23]. The frequency of this mode is found to be about 8 kHz (figures 7(a) and (c)). These modes are located just outside the inversion radius at the LFS (with an accuracy of 1.5–2 cm defined by the channel separation of the ECE diagnostic). No evidence of these modes at the HFS has been obtained so far.

The temperature contour plot in figure 7(a) shows a spike at the LFS ( $R = 2.72$  m) at about 7.038 45 s, indicating a very fast heat transfer ( $60 \mu\text{s}$ ) during the crash. This spike does not exist at the HFS (figure 7(b)) and, therefore, does not result from the helical distortion. A certain enhancement of temperature at  $R = 2.37$  m at the HFS can be explained by the imperfect calibration of this particular ECE channel (the second channel with an imprecise calibration is located at 2.62 m). However, the calibration error for this channel is as low as  $\pm 150$  eV (general measurement error  $\Delta T_e/T_e = 1\%$ ). Therefore, there is no doubt that the perturbation at  $R = 2.7$  m has a physical origin and is not an artefact of the measurement. The observed phenomenon is probably due to the highly asymmetric (poloidally and toroidally) ‘ballistic’ heat transfer and thought to be an indication of the magnetic field reconnection process that occurs at the LFS in this particular shot. It is important to recall that the ballistic effect implies the fast propagation of the plasma perturbations outside the  $q = 1$  surface just after the sawtooth crash [19]. These observations are also in agreement with measurements made at TFTR and DIII-D [5, 9, 19, 24].

On TEXTOR, an asymmetrical distortion of the displaced hot core has been observed in several sawtooth plasmas with moderate and high central densities and, in some shots, it is more pronounced, compared with Tore Supra. A ‘finger’-like perturbation at 2.1088 s (figure 8(b)) has also been detected; however, large radial spacing between ECE channels has made it impossible to see details of the fast heat pulse transfer. Very recently, observations of higher order perturbations on top of the  $m = 1$  precursor have been made by means of two-dimensional ECE-imaging [25]. Earlier on TEXTOR, a localized periodic perturbation of the magnetic field has been detected [26] which, in the presence of an  $m/n = 1/1$  island, may give rise to magnetic field line stochasticization [27] and thereby contribute significantly to a rapid expulsion of electronic energy from the plasma core region. However, no preferable phase (e.g. at the LFS or at the HFS) for the heat expulsion to appear has been detected on TEXTOR.

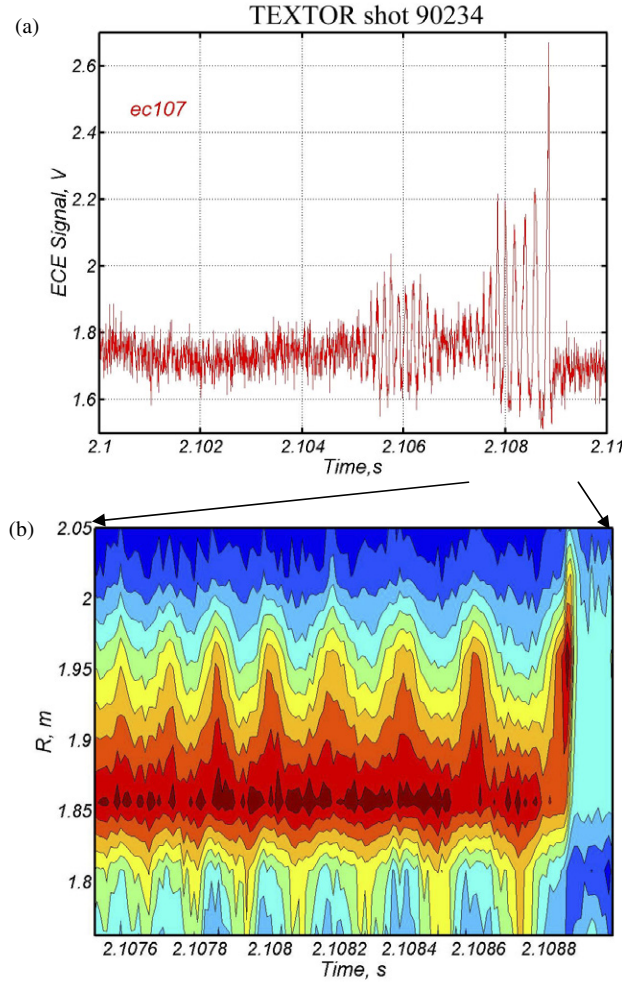
### 3.4. Topology of the $m = 1$ mode during the crash

The topology of the  $m = 1$  MHD mode before and/or after the sawtooth crash has been studied theoretically and experimentally in many tokamaks [1–5, 9, 24, 28–30]. Calculations performed by Sykes and Wesson [30] describe the phenomenon of the sawtooth crash as a two-structure (island) system, one with  $q < 1$  and another with  $q > 1$ , giving support for the Kadomtsev model. The island with  $q < 1$  (former hot core) decays away, displaced by the newly formed one with  $q > 1$ . Experimentally, a radially elongated or circular-shaped



**Figure 7.** Evidence for fast heat release outside the inversion radius at the LFS in a high density ICRH discharge on Tore Supra (same shot as in figure 1(d)). Here, (a) is the electron temperature contour plot with a solid arrow showing the fast heat pulse propagation during the crash and a dashed arrow showing some higher  $m$  oscillations near the mixing radius; (b) gives the electron temperature profiles at times shown by the solid arrow in (b). Plot (c) shows higher frequency oscillations on top of the  $m = 1$  precursor near the inversion radius, as seen by ECE.

shrinking hot core and a growing crescent-shaped  $m = 1$  island with the colder plasma has been observed at TFTR in high or moderate  $\beta_p$  plasmas by means of ECE and SXR [9, 24]. In contrast, in Wesson's quasi-interchange instability model [8], the formation of the crescent-like hot core and a 'bubble' of cold plasma is predicted in a  $q(r) \sim 1$  core region. Reconstruction

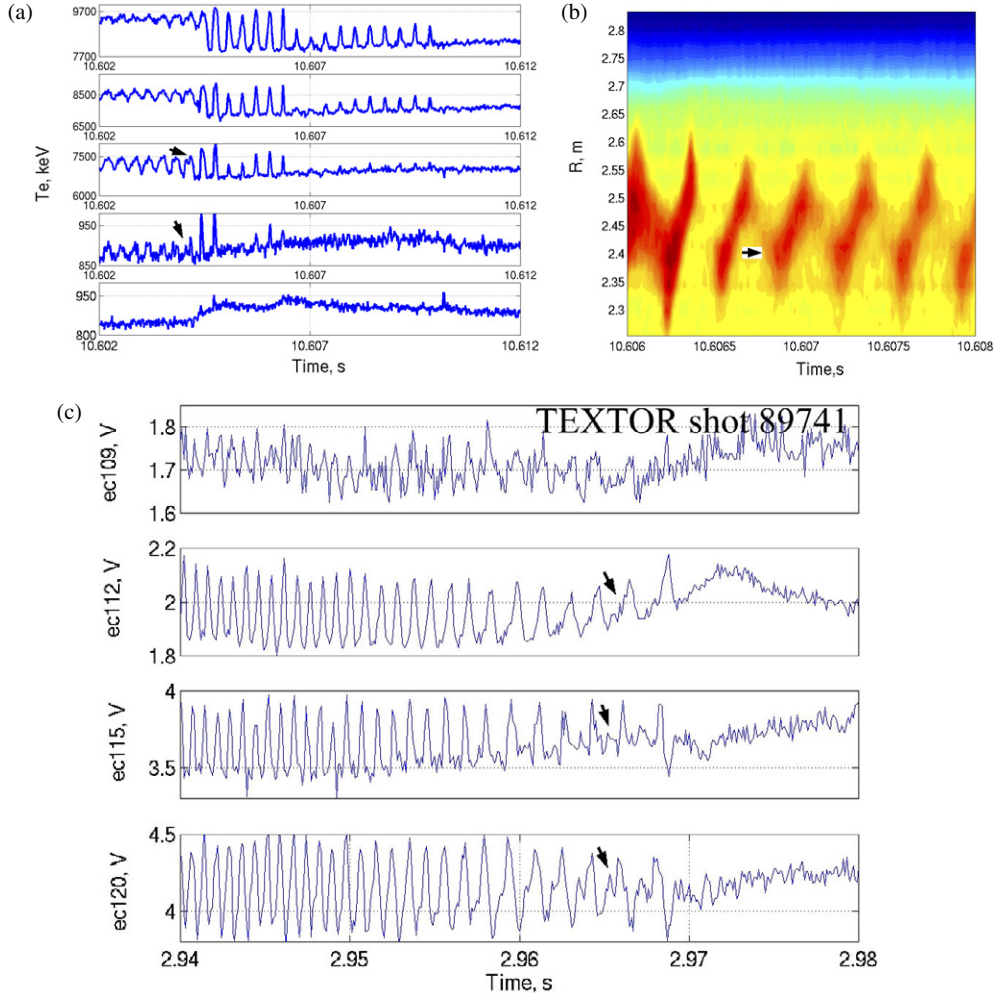


**Figure 8.** Evidence of the  $m = 1$  precursor LFS asymmetry on TEXTOR in an ECRH discharge: (a) typical time trace of an ECE channel located near the inversion radius, (b) contour plot obtained with the help of all available radial ECE diagnostics. Dark-red colour map corresponds to the hottest temperature of 2 keV.

of the contours of constant SXR emission in JET [31] revealed the structure predicted by Wesson for ideal kink instability; however, no precursor oscillations were present in these shots. Recently, observations of the sawtooth crash by means of a few SXR cameras on the WT-3 tokamak have shown that the core is displaced from the magnetic axis and is reshaped into a thin crescent aligned along the inversion circle [29]. Yet, under different plasma conditions in different tokamaks, no clear and consistent picture of the  $m = 1$  mode topology has been found. Moreover, some observations are in conflict with one another or with theoretical predictions. At Tore Supra the topology of the  $m = 1$  mode has been studied by means of ECE, SXR and, partially, by reflectometer diagnostics. At TEXTOR a combination of various radial and vertical ECE diagnostics has been utilized for the same purpose.

Figure 9 shows rich harmonic content on time traces close to the inversion radius on Tore Supra (a) and TEXTOR (c), similar to what has been observed on the FTU tokamak





**Figure 9.** Black arrows show a change in the oscillation phase on the ECE time traces near the inversion radius on Tore Supra before the first crash at 10.6045 s ((a) shot #32763). Plot (b) shows a certain asymmetry of temperature contours for the displaced hot core at the fixed radius at about 10.607 s. The colour map is exactly the same as in figure 7(a). Rich harmonic content near the inversion radius also has been observed by ECE on TEXTOR (black arrows in (c)).

for snake-like sawtooth precursors in discharges with pellet injection (however, FTU plasmas have much higher  $Z_{\text{eff}}$ ) [28]. This is an indication that the displaced hot core is reshaped and becomes asymmetric before the crash, or that there is a temperature peaking inside the newly formed island [9, 16] on the former magnetic axis. A contour plot of the  $m = 1$  precursor on Tore Supra shown in figure 9(b) shows a distortion of temperature contours for the displaced hot core at the fixed radius.

In order to develop a poloidal two-dimensional reconstruction of the  $m = 1$  precursor using ECE data, the projection of the toroidal mode rotation on poloidal cross-section for a single period before the crash (to ensure that precursor amplitude is no longer growing) has been taken for the shot in figure 1. The component that comes from the purely poloidal mode rotation is assumed to be negligibly small [32, 33]. A simple analytical equilibrium with



Shafranov shift has been assumed for the coordinate transformation

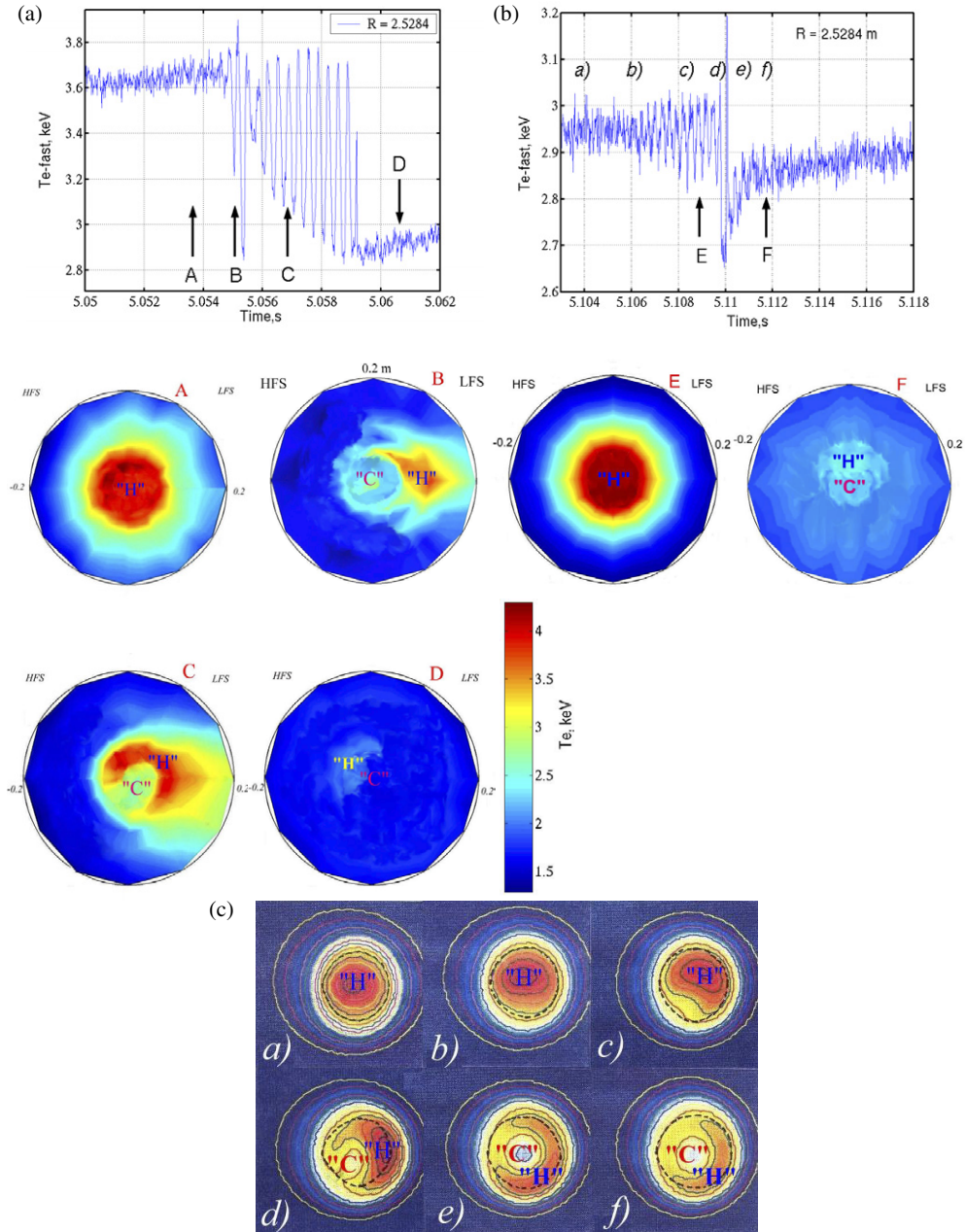
$$\Delta(\psi) = \Delta_0 \left[ 1 - \left( \frac{r'}{a} \right)^2 \right], \quad (2)$$

where  $\psi$  is the flux surface at the given position ( $r'/a$ ),  $\Delta(\psi)$  is the shift of this flux surface and  $\Delta_0$  is the displacement of the axis (typically 5–8 cm for both machines).

Figure 10(a) shows the topology of the second kind of  $m = 1$  precursor behaviour. It appears that the hot core (labelled 'H') is slightly shifted off-axis at time A, but is still circular-shaped. The fast displacement of the hot core occurs as shown at the time B, and reshaping into the hot (poloidally elongated) crescent-like structure is finally completed at time C. A certain bulge in the displaced hot core towards the LFS is an artefact of the reconstruction. Near the former magnetic axis, a structure with colder plasma is formed (label 'C'). Usually, the temperature of the hot core stays unchanged during the precursor evolution or even decreases somewhat (by 5–10% in several shots) during the evolution of the second kind of the precursor activity. During the crash, the heat from the displaced hot core quickly dissipates, and no or very weak (in amplitude) oscillations are detected after the crash for this time of the shot (time D). Evolution of the first kind of  $m = 1$  precursor before and after the crash (labels E and F, respectively) is given in figure 10(b). During the crash event itself, the shape of the hot core is similar to this for the second kind of  $m = 1$  mode behaviour. The postcursor activity (time F), however, is much more pronounced compared with D.

It is important to mention that the two-dimensional reconstruction of the mode topology from one-dimensional ECE measurements may give an uncertainty in the determination of the shape of the displaced hot core. To distinguish between circular or poloidally-elongated (bean or crescent-like) shapes of the hot core, additional information about difference in phase for mode oscillations between LFS and HFS, dimensionless temperature  $\Delta T_e/\bar{T}_e$  as well as help from other diagnostics are needed. However, figures 9 and 10(a) at time B show clearly that, in these shots, the hot core may deviate from circular shape during its fast displacement off the magnetic axis.

Observations by two SXR cameras at Tore Supra for a similar discharge with sawteeth as in figure 10(b) (low- $Z_{\text{eff}}$  deuterium plasma) have shown the formation of the crescent-like structure out of the former core (figure 10(c)) [11]. The SXR camera setup allows us to distinguish two components of the  $m/n = 1/1$  mode and one component of the  $m/n = 2/1$  mode. In this particular case the  $m = 1$  mode was propagating at the poloidal angle of  $45^\circ$ . Additional information from the ECE radiometer that is toroidally separated from SXR by  $180^\circ$  has been used to identify the radial position of the displaced hot core in the course of time and, thus, for a proper tomographic reconstruction. It has been detected that the sudden radial shift (as observed in the poloidal cross-section) of the circular hot core takes place during just  $50 \mu\text{s}$ , with a radial velocity of  $2\text{--}3 \text{ km s}^{-1}$  (figures 10(b) and (c)), and accompanied by an increase of density fluctuations. The wave number of these fluctuations,  $k$ , is estimated to be  $4 \text{ cm}^{-1}$  from coherent scattering measurements (laser  $\text{CO}_2$ ,  $\lambda = 10.6 \mu\text{m}$ ) [34]. Because SXR radiation is proportional to  $n_e^2 T_e^\alpha$  ( $\alpha > 0.5$ ) [35], high emission can be expected where the temperature and the density are high or if there are many impurities in the plasma. In shots reported here,  $Z_{\text{eff}}$  is about 2.5 and does not change in a course of the sawtooth. The electron density in the hot core does not change much in a course of the precursor evolution, and rises slightly by only 0.1%, as evidenced from interferometer measurements. Unfortunately, the present interferometer on Tore Supra is slow (sampling rate  $< 1 \text{ kHz}$ ), and has only three viewing chords that cross the plasma core inside the inversion radius. Thus, no detailed local evolution of the density profile can be deduced from the measurements. Nevertheless, it seems quite obvious that the highest SXR emission on the reconstruction corresponds to the displaced hot core. The shifted hot



**Figure 10.** ECE poloidal reconstruction of the  $m = 1$  mode topology for Tore Supra: the first kind (a) and the second kind of precursor behaviour (b). Letters A–F correspond to different reconstruction times. Labels ‘H’ and ‘C’ match the hot core and the cold island, respectively. A certain extension of hot contours towards the LFS in (b) and (c) is an artefact of the reconstruction. Note a difference in the postcursor activity at times D and F. Plot (c) gives the evolution of the  $m = 1$  precursor to sawtooth at Tore Supra [11], as observed by SXR tomography. Set of reconstructions (a–f) corresponds to the times in (b). Regions with high SXR emission are shown in red, while yellow and blue correspond to lower emission.

core is reshaped into a crescent and a newly formed cold ‘bubble’ is placed on the former magnetic axis (figure 10(d)). One can think about the magnetic configuration that consists of two structures that exhibit themselves by higher and lower SXR emission levels. Later, the emission from the crescent falls, and the size of the ‘cold bubble’ increases significantly (figures 10(e) and (f)). The formation of a crescent-like structure out of the former hot core has also been observed on the WT-3 tokamak [29].

The present two-camera SXR set on Tore Supra does not allow us to distinguish the real profiles of emission from the centre of cold ‘bubble’ [36]. In several models [1, 4, 5, 9, 28, 30], the cold ‘bubble’ is explained as a  $m/n = 1/1$  magnetic island with a typical tearing mode structure. Evidence that favours the ‘tearing mode’ origin of a cold ‘bubble’ on Tore Supra has been obtained in some plasmas by means of fast fluctuation reflectometers and ECE.

As has already been mentioned in section 3.1, there are a few shots in which  $m = 1$  mode oscillations are still present after the crash with the second precursor type. Figure 11 shows oscillations as measured by the fluctuation reflectometer and ECE immediately after the second crash type. The sampling rate of the reflectometer is higher than that of ECE. Reflectometer and, to a lesser degree, ECE data show the presence of a frequency component that is twice as high as the frequency of the  $m = 1$  before the crash. This effect can be caused by a secondary density and temperature peaking inside the ‘cold island’, implying that there is an improvement of the plasma confinement inside (compared with the background plasma), similar to what has been observed for  $m/n = 2/1$  magnetic islands in TEXTOR [32]. In several discharges similar double-frequency oscillations are observed before the crash, too. In other shots a clear flattening of the electron temperature profile inside the cold island is observed before the sawtooth collapse.

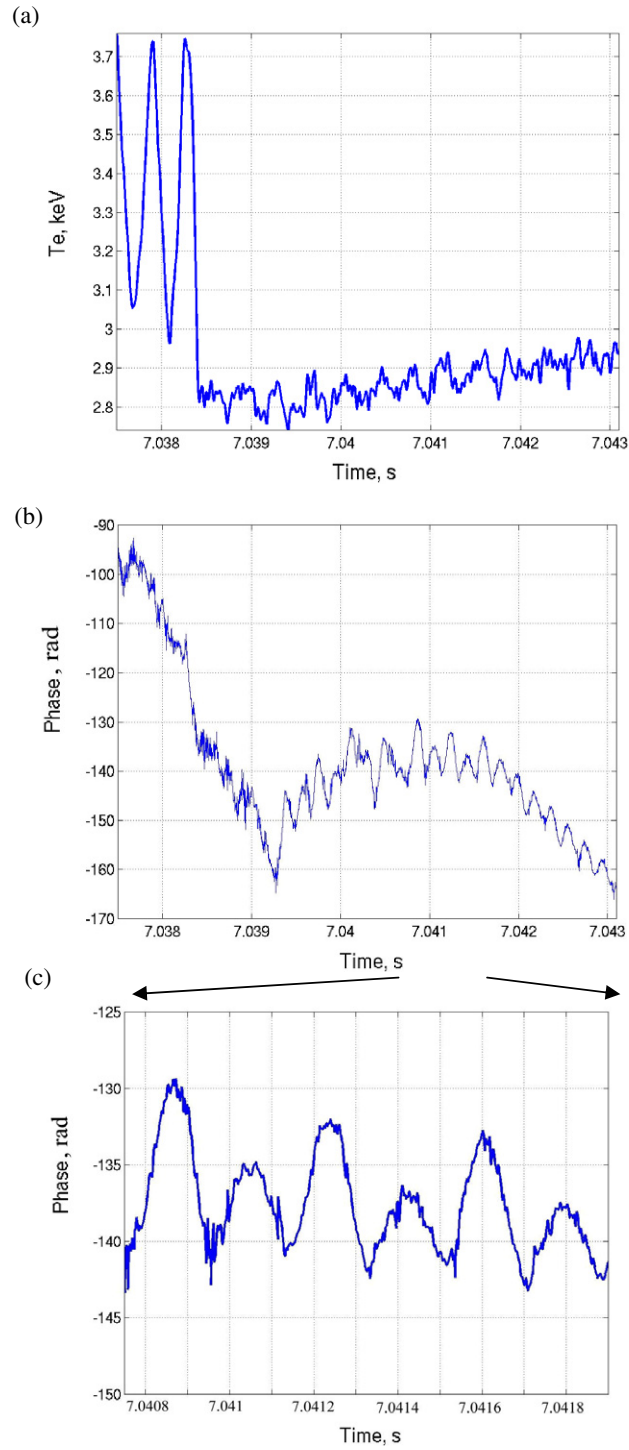
Observations proving that the hot core gets displaced and forms the hot crescent or bean-like structure surrounded by the colder plasma were made recently at TEXTOR tokamak using the combination of ECE data from poloidal and radial diagnostics [37, 38]. The poloidal two-dimensional reconstruction of the  $m = 1$  precursor with large amplitude of oscillations is shown in figure 12. It suggests a strong similarity of the  $m = 1$  mode evolution during the sawtooth activity between two tokamaks.

The question of how precisely the reshaping of the displaced hot core into the ‘crescent’-like structure occurs is still open. From a non-linear simulation with the reduced MHD model [39] of the internal kink with single helicity,  $n = (0-14)$ , and  $\tau_R/\tau_A \times 10^{-6}$ , formation of the crescent-shaped structure is seen on a pressure contour plot (figure 13). The current density distribution is peaked near the X-point of the  $m/n = 1/1$  ‘cold’ island and is similar to what one expects from the Kadomtsev model for the sawtooth crash.

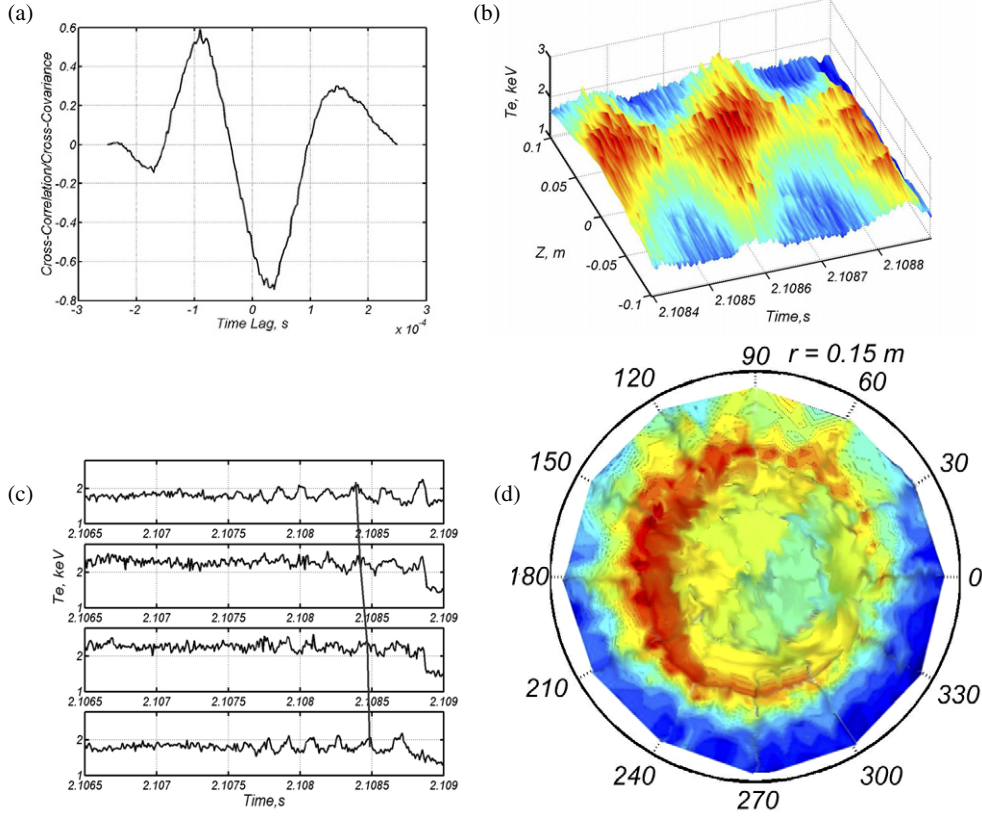
Another potential explanation can be given if one considers the ‘positive’ magnetic island concept [7, 40]. It has been shown in [7] that in low magnetic shear configurations or in the case of strong current perturbations with a high current density, positive islands can form in local regions with positive current modulation together with the usual negative islands, in which the modulation of the perturbation current is negative. When the magnetic shear is sufficiently low and if the positive modulation  $j_\theta^+$  is large enough,

$$j_\theta^+ > \langle j \rangle_r \frac{r}{q} \frac{dq}{dr} \quad (3)$$

a positive island can develop and should be radially aligned, unlike conventional negative islands, which are positioned in the poloidal direction. Under certain conditions, however, the positive island can be reshaped into a crescent. This may occur if the positive current perturbation has the feature of a dipole-like current sheet (e.g. consists of two components with different signs) with width  $r$  and length  $L$  (in the  $\varphi$  direction),  $L \gg r$ , and if this



**Figure 11.** Oscillations after the crash with the second type of  $m = 1$  mode behaviour are detected for the shot #32178 on Tore Supra. The middle trace represents data from the fluctuation reflectometer that monitors the plasma inside the  $q = 1$  radius at  $R = 2.35$  m (the quantity plotted on Y-axis is the wave phase delay in radians [12]), the lower trace is ECE at the same radial position. The ECE time trace has been smoothed by a spline.



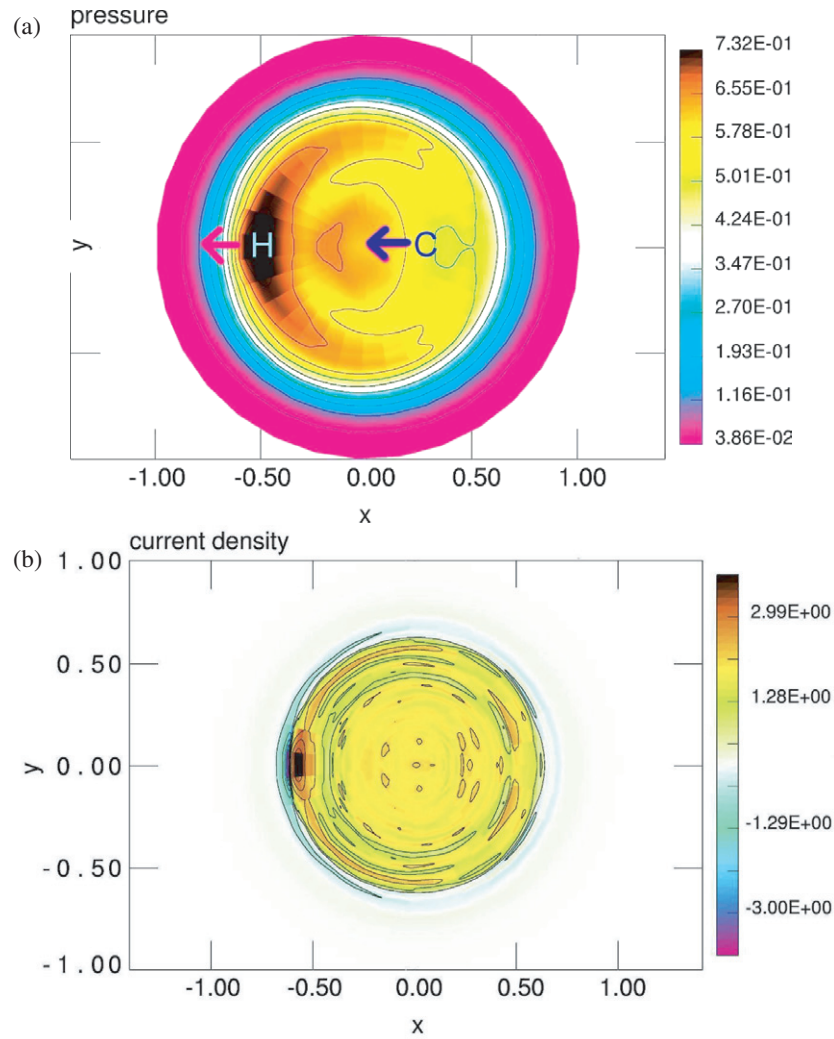
**Figure 12.** From the cross-correlation between two ECE-imaging channels above (# 14) and below (# 3) the equatorial plane at TEXTOR, displaced by 18 cm (a), the MHD frequency and the projected poloidal rotation velocity of the  $m = 1$  precursor before the crash are estimated to be about 4.2 kHz and  $2 \text{ km s}^{-1}$ , respectively. A surface plot (b) shows that temperature profiles are ‘bending’ around  $Z = 0$ . An asymmetry can also be seen on time traces ((c) channels 3, 8, 10, 13). A curved line shows the propagation of the ‘hot spot’ of the precursor. From the poloidal reconstruction (d), it can be seen that the  $m = 1$  has an elongated shape, and it is displaced with respect to the midplane. Oscillations with higher frequencies are probably caused by an artefact induced by an imperfect calibration of the ECE-imaging. Contour smoothing has been used to improve the quality of the figure [37, 38].

perturbation exists outside the resonance surface. In this case, equation (3) can be rewritten for the crescent-like geometry as

$$j \geq \frac{2.5}{\pi} B_\phi \frac{dq}{dr} \frac{1}{q} \quad (3a)$$

in which  $B_\phi$  is the perturbation field. However, a really good estimation or measurement of the  $q$ -profile and of the magnetic shear in the plasma centre as well as information about the perturbation of the magnetic field in the vicinity of the  $q = 1$  surface are needed in order to apply the positive magnetic island concept to explain the behaviour of the  $m = 1$  mode before the sawtooth crash.





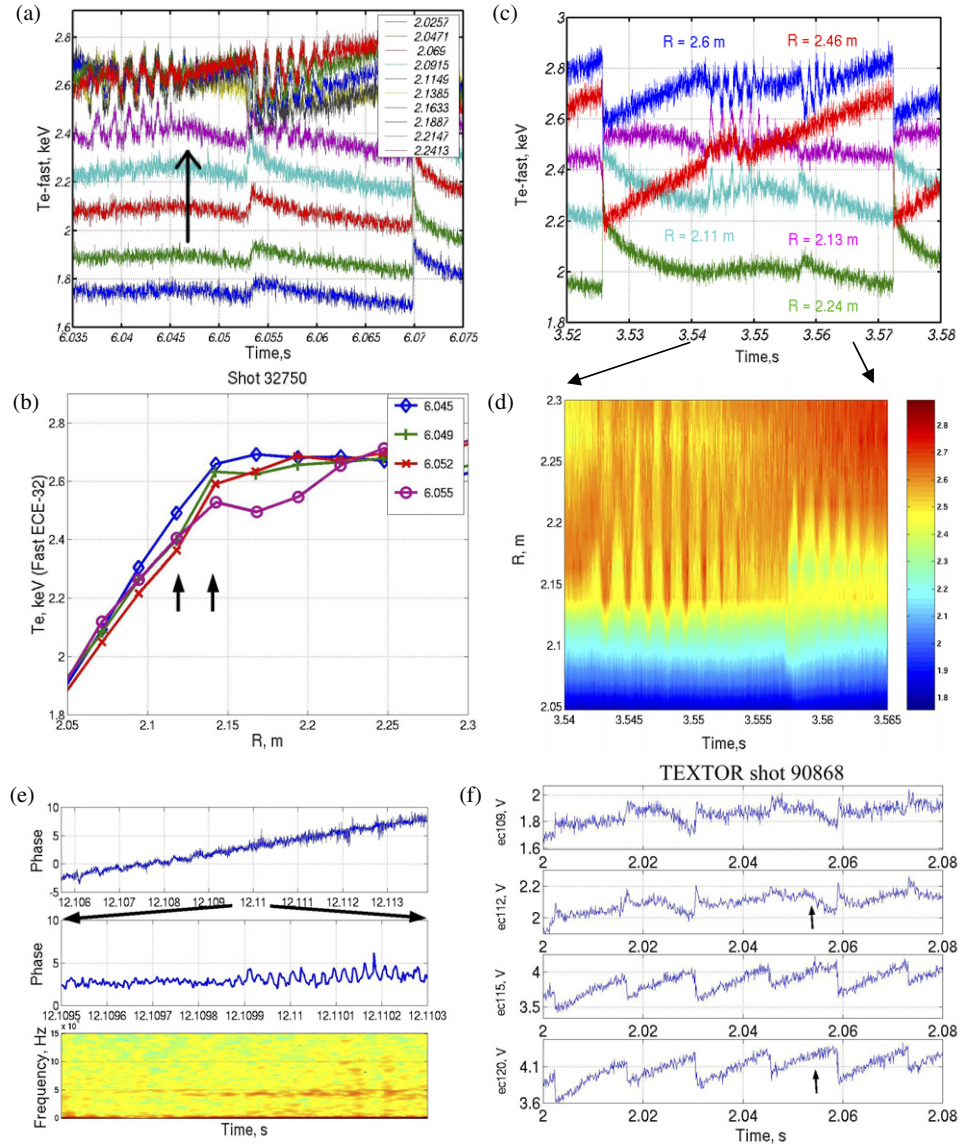
**Figure 13.** Formation of a crescent-shaped structure in pressure in the poloidal cross-section (a) out of the former hot core (labelled 'H') as a result of non-linear simulation with the reduced MHD model of the internal kink with single helicity. Label 'C' corresponds to the 'colder' island. The  $Y$ - and  $X$ -axes are normalized to the minor radius. The current density distribution is shown in (b).

### 3.5. Compound crash: evidence for a transport barrier at the $q = 1$ surface

Figure 3(a) shows a typical compound crash on Tore Supra with oscillations similar to the second manifestation of  $m = 1$  mode behaviour. These oscillations survive the 'mid'-crash; however, their amplitude continuously decreases as the central temperature rises. Oscillations of the  $m = 1$  mode are clearly seen on all channels inside the inversion radius. It is an obvious indication that  $q_0$  remains below 1 after this 'mid'-crash and only incomplete reconnection takes place.

However, there is another manifestation of the 'mid'-crash that is frequently observed on Tore Supra and TEXTOR. An interesting study of the central electron temperature behaviour has been made for the cases shown in figures 14(c) and (d) and figure 3(b). It can be seen that,





**Figure 14.** Evidence of the  $q = 1$  radius shrinking on Tore Supra (a): after oscillations disappear at 6.045 s (black arrow), the temperature at  $R \leq 2.115$  m (magenta line) drops significantly, compared with central channels. The black arrows in (b) show the electron temperature gradient steepening and give an indication of a transport barrier at the  $q = 1$  surface, as this surface moves inwards. Plots (c) and (d) give evidence that the plasma in the centre (red trace) is excluded from the reconnection process. Interestingly, at 12.11 s, a fast 45 kHz mode is detected in the plasma centre by the reflectometer soon after the minor crash (e). A spectrogram at the bottom is related to the upper plot in (e). On TEXTOR, formation of a barrier in the MHD-free plasmas has been observed during off-axis ECRH (f).

unlike the ‘usual’ crash, the electron temperature on the magnetic axis has not been affected by the compound crash and continues to rise. However, channels that measure closer to the inversion radius have observed the crash event. This observation implies that the reconnection process of a few flux surfaces takes place in a layer close to the inversion radius. The central part is, therefore, excluded from the reconnection, in agreement with results reported in [24]. It is very likely that a double  $q = 1$  surface (and  $q_0 > 1$ ) exists in these plasmas, although, no direct measurements of  $q(r)$  have been performed on Tore Supra for these shots by means of motional Stark effect (MSE) and polarimetry diagnostics. Experimental confirmation that a double  $q = 1$  surface exists in similar discharges has been obtained on TEXTOR [41].

Evidence for an internal transport barrier associated with the  $q = 1$  rational surface has been obtained before the compound crash event both in Tore Supra (LHCD, Ohmic plasmas) and TEXTOR (ECRH plasmas). It can be seen as a sudden change in the electron temperature gradient from  $|dT_e/dr| = 5.5 \text{ keV m}^{-1}$  at 6.045 s to  $|dT_e/dr| = 9.4 \text{ keV m}^{-1}$  at 6.049 s (figures 14(a) and (b)). This barrier-like feature is not an artefact of reduced MHD, since there are examples in which no or just a very small  $m = 1$  mode presents, however, the formation of a steep temperature gradient still occurs (figure 14(f), TEXTOR).

In this time window the radius of the  $q = 1$  surface shrinks and passes through several neighbouring ECE channels. In particular, a channel at  $R = 2.13 \text{ m}$  (magenta colour in figure 14(c)) exhibits inverted sawtooth behaviour during the ‘main’ crash at 3.525 s and 3.572 s; however, during the ‘mid’-crash at 3.557 s, it obviously monitors the plasma inside the  $q = 1$  radius. The effect of the shrinking  $q = 1$  radius is clearly seen in the contour plot in figure 14(d). Central temperature rises during the same time period. This phenomenon is more pronounced in Tore Supra in plasmas with LHCD, in which flat or even hollow central current density profile is expected.

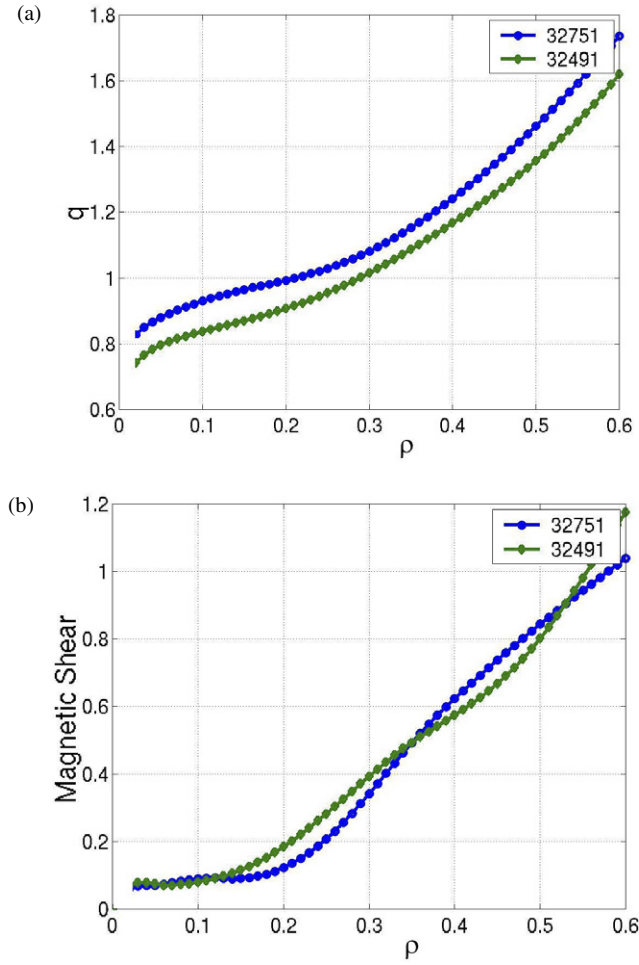
During the formation of the transport barrier in the same discharges, the presence of the high frequency mode is detected on Tore Supra by the fluctuation reflectometer and correlation ECE. These fast oscillations (up to 45–50 kHz) are observed soon after the ‘mid’-crash, when the  $m = 1$  mode has disappeared (figure 14(e)). Temperature profiles in this phase are similar to those in figure 14(a). Possibly, these modes can be identified as geodesic acoustic modes (GAMs) [42]:

$$f_{\text{GAM}} = \frac{c_s}{2\pi R_0} = \frac{\sqrt{(T_e + T_i)e/M_i}}{2\pi R_0} \approx 50 \text{ kHz} \quad (4)$$

in which  $T_e = 4 \text{ keV}$ ,  $T_i = 2 \text{ keV}$  and  $R_0 = 2.45 \text{ m}$ . The frequency of GAMs should depend on the value of  $T_e$ ; however, up to now, there are not enough shots to draw a definite conclusion. More dedicated studies of density and temperature fluctuations in the vicinity of the  $q = 1$  surface will be made in Tore Supra with the fluctuation reflectometer and the newly installed correlation ECE radiometer [23] during future experimental campaigns.

#### 4. Simulations of the $q$ -profile during sawtooth activity in Tore Supra

In order to make a proper estimate of the  $q$ -profile evolution during various crash types at Tore Supra, simulations with the integrated modelling code CRONOS have been performed. This code solves the one-dimensional transport equations and self-consistently calculates the plasma equilibrium, bootstrap current and the various heating and current source terms [43]. Figure 15 shows the CRONOS reconstruction of the  $q$  and magnetic shear profiles for two shots, with LHCD (shot #32491, the first kind of  $m = 1$  precursor behaviour) and ICRH (shot #32751, the second kind), just before the crash itself. Unfortunately, because real plasma profiles are taken with relatively large time steps (tens of milliseconds) and because error



**Figure 15.** CRONOS simulations for two Tore Supra discharges in which ICRH (32751) and LHCD (32491) power has been injected, for  $q$  and  $(\rho/q)\partial q/\partial\rho$  before the sawtooth crash with different  $m = 1$  mode activity types. Here,  $\rho$  is the dimensionless flux function. Note a significant difference in the central shear value distribution between these shots. Vertical dashed lines show that the region for  $\rho < 0.02$  contains significant error bars for  $q$  and  $\partial q/\partial\rho$ .

bars for the  $q$  values can be considerable, there is no possibility of following fast changes in  $q$ -profiles, and only a qualitative analysis can be made.

It can be seen that in both cases the magnetic shear is low near the plasma centre; however, the low shear region is large for the shot with ICRH and favours the larger radial size of the  $m = 1$  mode. The second type of precursor manifestation exists in the shot with  $q_0$  somewhat closer to 1 before the crash, compared with the first type of mode behaviour. Note a certain decrease in central  $q$  values for  $0.02 < \rho < 0.05$ , where  $\rho$  is the flux function. Owing to a numerical artefact because of internal fitting procedures, values of  $q(\rho)$  and magnetic shear for  $\rho < 0.02$  are not to be trusted. EFIT [44] calculations for the same Tore Supra shots yield similar results.

On TEXTOR,  $q(r)$  profiles measured by means of polarimetry in Ohmic discharges with sawteeth have shown that the central value of safety factor remains below 1 after the crash, and the relative change during the crash equals about 8% [2].

Interestingly,  $q$ -profiles in Ohmic and ICRH phases, where only the first kind of  $m = 1$  mode behaviour has been observed, have shown similarity to the  $q$ -profile during LHCD. This means that sudden local modifications of the current density profile and, therefore,  $q(\rho)$ , lead the  $m = 1$  mode to manifest itself quite differently before or after the sawtooth crash.

## 5. Conclusion

Experimental observations of the  $m = 1$  mode during sawtooth activity on Tore Supra and TEXTOR have shown two different kinds of precursor manifestations in terms of the size of the hot core displacement and the duration of the oscillating phase. Generally, the evolution of the  $m = 1$  precursor on both machines can be described as follows. It starts with a kink-like perturbation that displaces the circular hot core off the magnetic axis. The initial shift is about 2–3 cm. This phase can last until very close to sawtooth collapse, when the hot core experiences a further shift by 5–8 cm and the heat dissipation occurs. In many cases, however, oscillations may continue after the crash without any significant changes in the temperature and density of the displaced hot core. These oscillations last up to several milliseconds, and the former hot core displacement may stay constant or increase steadily until the second crash. Moreover, it has been observed that the displaced hot core may survive a few successive crashes. The island with the colder plasma inside is taking the place of the former magnetic axis. Qualitatively, the evolution of the  $m = 1$  precursor is as predicted by Kadomtsev [1] and Sykes and Wesson [30]; however, a few discrepancies arise when the quantitative and topological analysis is made. The crash times are found to be shorter, and the post-crash  $q_0$  remains below 1. In many shots, postcursor oscillations are present, indicating that the reconnection process is not completed during the crash. Only a very few examples show no postcursor activity. However, the duration of the postcursor phase or its absence depends on the  $q$ -profile evolution in the plasma centre, as evidenced from numerical simulations on Tore Supra and polarimetry measurements on TEXTOR.

As can be seen from topological reconstruction, the shifted hot core may deviate from circular, especially if the radial displacement is high. Though a crescent or bean-like poloidal elongation of the former hot core may take place, a ‘quasi-interchange’ model proposed by Wesson [8] is very unlikely to occur in both Tore Supra and TEXTOR cases, mainly because the value of  $q_0$  remains below 1 during the whole sawtooth period. During the heat dissipation phase, evidence of the higher order modes at the LFS, most likely of ballooning origin, has been obtained on Tore Supra. The presence of these modes may lead to ergodization of the magnetic surfaces near the inversion radius, and, therefore, to the modification of the heat transport. The observed heat transfer during the crash is ballistic in its nature. The fast (60  $\mu$ s) heat pulse propagation during the crash seen by ECE is thought to be a hint of the magnetic field reconnection process.

Investigations of the so-called compound or ‘mid’-crash with the oscillating  $m = 1$  mode have shown evidence of the double  $q = 1$  surface in the plasma centre. In several cases formation of a steep electron temperature gradient before the compound crash is seen on both machines, indicating the formation of the internal transport barrier that is associated with the  $q = 1$  rational surface. The presence of the high-frequency mode (most likely GAM) is detected on Tore Supra during the formation of the barrier before the ‘mid’-crash; however, its influence on the evolution of the barrier is still under investigation.

In future experimental campaigns at Tore Supra and TEXTOR, dedicated studies of plasma transport properties in the vicinity of  $q = 1$  surface will be made. On Tore Supra, we will concentrate on plasma turbulence measurements in different heating regimes (LHCD, ICRH and ECRH) by means of density fluctuation reflectometer and correlation ECE. Measurements of the  $q$ -profile will be made with calibrated MSE and polarimetry diagnostics. On TEXTOR, temporal evolution and the topology of the fast  $m = 1$  precursor to sawteeth will be investigated in detail by means of a newly installed two-dimensional ECE-imaging diagnostic [25] and a set of several SXR cameras [45].

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